

A Hidden Nucleus in Cygnus A, but Not in M87

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Received _____; accepted _____

ABSTRACT

Historically the narrow line radio galaxies were thought to be intrinsically nonthermal, and without significant accretion. When the Unified Model came along the compelling observational motivation for this lost some force: some are found to be *hidden* broad line objects, and in principle that could be the case with all of them. The clear sign of a hidden quasar is a normal quasar spectrum in polarized (scattered) light. However that test requires a suitably placed “mirror.” A more robust test is the high predicted mid-IR core luminosity reradiating from the obscuring matter. Cygnus A has this component, but M87 does not.

Subject headings: galaxies: active — galaxies: individual (M87, 3C 405) — galaxies: nuclei — infrared: galaxies

1. Introduction

Now that the existence of supermassive black holes in AGN seems fairly secure, perhaps the next most fundamental questions are the source of energy and nature of the accretion flow in the various classes of objects. Historically (see Begelman, Blandford and Rees 1984 for an early review) it was thought that the optical/UV continuum (the “Big Blue Bump”) in quasars (hereafter: and broad line radio galaxies) was thermal radiation from some sort of cool optically thick accretion flow. Radio galaxies didn’t show this component, so were posited to be “nonthermal AGN” with hot radiatively inefficient accretion at a very low rate, with the jet power deriving from the hole rotation rather than accretion, perhaps via the Blandford-Znajek (1977) mechanism.

One Fanaroff-Riley II (edge-brightened, very luminous) radio galaxy, 3C234, was shown in 1982 to have quasar features (broad permitted emission lines) in polarized light

(Antonucci 1982, 1984; Antonucci 1993 for a review). Thus it does have the “thermal” Big Blue Bump, which is only visible via scattering. Many other examples have been shown subsequently (e.g. Hines and Wills 1993, Young et al. 1996). Some invocations of the Unified Model postulated that this was also true of the FR II (powerful, edge-brightened) class generally (e.g. Barthel 1989). However, it is still contentious how those FR IIs with weak and/or low ionization narrow emission lines fit in (Antonucci 2001, Singal 1993, Laing 1994, Gopal-Krishna et al. 1996). The situation for the FR I galaxies, almost all of which have undetectable or low-ionization emission lines, is even less clear. Where there is no observable high-ionization narrow emission line region present, there is no *a priori* evidence for the presence of a quasar. These could still have a quasar nucleus, but any narrow line region would need to be mostly obscured as well. That seems to be the case for NGC4258 (Wilkes et al. 1995, Barth et al. 1999).

Many FR II radio galaxies fall into the weak, low-ionization category. *Most* of the FR I radio galaxies do as well. Among these objects a majority show optical/UV point sources, while a significant minority do not (Chiaberge et al. 1999, 2000). The galaxies known from spectropolarimetry to harbor hidden thermal nuclei generally do not show point sources, but just extended emission from the mirror. (3C234 is an exception, though it also has some extended flux.) How can we tell whether or not a hidden nucleus is present? Many hidden AGN that are not Compton-thick have been discovered with X-ray observations (Antonucci 2001); NGC4945 is a spectacular example (Madejski et al 2000). Detection of broad lines in the polarized flux spectra indicates robustly the presence of a hidden normal quasar (or broad line radio galaxy). But this test requires fortuitous placement of a natural scattering mirror. A much more complete test is to measure the reradiation from nuclear hot and warm dust — which almost necessarily accompanies any hidden AGN. Unlike spectropolarimetry this method measures the “waste heat” and so provides an estimate of the hidden luminosity. We’re half-way through a major survey of the 3C radio galaxies in

the mid-IR with Keck, and thought the results for M87 and Cygnus A were worth showing now.

2. Observations

2.1. 3C 405 (Cygnus A)

We present a diffraction limited mid-IR image of the nuclear source in 3C 405 (Cyg A), obtained with the Long Wavelength Spectrometer (LWS) instrument at the Keck telescope*. All data were taken with the $11.7\mu\text{m}$ filter, which has an $\sim 1\mu\text{m}$ bandpass from 11.2 to $12.2\mu\text{m}$.

The nucleus of 3C 405 was imaged at $11.7\mu\text{m}$ with Keck/LWS on 1999 September 30. The chop/nod throw was set to $10''$ in order to allow imaging of larger scale extended structure; this places the negative images off the chip, which has a $10''$ field. We do not report on structures larger than the $10''$ chop distance. The images were dithered in a 5 position box pattern, $2''$ to a side, with 53.1 seconds on-source for the positive image per dither position. The entire 5-position exposure was repeated three times, for a total on-source time of 796.6 seconds.

Data were processed by subtracting all background chop/nod frames, shifting each dithered image to the correct position, and coadding all dither images. Morphology is extended, with structure to the east and southeast of the nucleus (Fig. 1). The standard star was alpha Ari[†], with a FWHM of $0.27''$.

Table 1: LWS photometry results for Cygnus A:

aperture diameter (arcsec)	flux (mJy)
0.64	44
0.96	71
1.28	93
1.60	111
1.92	122
2.56	139
3.20	152

For comparison, the IRAS (large aperture) data for Cygnus A are listed in Table 2.

Table 2: (Impey and Neugebauer 1988):

12 μ m	$S = 144 \pm 5$ mJy
25 μ m	$S = 870 \pm 5$ mJy
60 μ m	$S = 2908 \pm 13$ mJy

There is Galactic emission contamination at longer wavelengths.

Our 11.7 μ image and a partial spectral energy distribution are shown in Figs. 1 and 2.

2.2. 3C 274 (M87)

Similar imaging data were obtained for M87 on 2000 January 18. The instrument was observed in chop-nod mode using a small 3.5" amplitude so as to keep both the positive and negative images on the CCD chip.

The same dither pattern was used, with 96 seconds per dither each for positive and negative (background). Unfortunately, due to a loss of guiding, the positive nucleus image was only fully imaged in one dither frame.

Beta Andromedae and Mu Ursae Majoris were used as standard stars for photometric calibration, yielding a flux scale of 0.0874 and 0.0931 mJy/(ADU/s) and FWHM of 0.33" and 0.31" respectively. Applying this photometric calibration to the unresolved nuclear component in M87 results in a flux of $13 +/ - 2$ mJy. The uncertainty is dominated by systematic errors in the background subtraction; we conservatively adopt a value of 15 mJy. A synthetic aperture of 0.96 arcsec was used, but the source is unresolved so the flux is insensitive to the aperture.

The IRAS fluxes are listed here: (Moshir et al. 1990).

Table 3.

$12 \mu\text{m}$	$S = 231 +/ - 37$ mJy
$25 \mu\text{m}$	$S < 241$ mJy
$60 \mu\text{m}$	$S = 393 +/ - 51$ mJy

3. Discussion

3.1. Cygnus A

This is a very powerful FR II radio galaxy at a redshift of 0.056. It has strong high-ionization narrow lines, suggestive of a hidden AGN. A broad Mg II 2800 emission line is detectable in total flux (Antonucci et al. 1994). That line may or may not be highly polarized, and thus scattered from a hidden nucleus. Several detailed papers report spectroscopic and spectropolarimetric data (Goodrich and Miller 1989, Tadhunter et al.

1994, Shaw and Tadhunter 1994, Vestergaard and Barthel 1993, Stockton et al. 1994; see also Tadhunter et al. 2000 and Thornton et al. 1999 - and there are several others), culminating in Ogle et al. 1997, which shows an extremely broad H-alpha line in polarized flux. It is virtually invisible in total flux.

A nuclear point source in the near-IR was noted by Djorgovski et al. (1991), but they don't seem to have considered hot dust emission for this excess over the extrapolation of the optical light.

A powerful hidden nucleus should manifest a mid-IR dust luminosity much larger than the observed optical luminosity. However for this object and M87 (and virtually all others!) the only IR data available were taken with very large beam sizes[†]. We isolate the core much better with the ~ 0.3 arcsec = ~ 1.1 kpc resolution provided by the Keck telescopes, and find a nuclear flux of ~ 71 mJy. An uncertainty here derives from the extended emission, but flux as a function of aperture size does flatten out for apertures larger than the seeing disk, so the 0.96" measurement should be approximately correct (see Table 1). However, we can't be sure from this observation alone that the emission is on pc scales. Since the emission is powerful and at the relatively short wavelength of 11.7μ , it is very likely that this comes from nuclear dust rather than a starburst.

The IRAS (large aperture) dust spectrum is quite cool, suggesting a large starburst contribution. Extended emission is seen in our image at 11.7μ but for the present purpose we want the nuclear flux. The core can't be exactly separated from the extensions (see Table 1), but we can estimate around 60 mJy for an unresolved core. Fig. 1 shows the Cyg A 11.7μ image, and Fig. 2 shows a partial spectral energy distribution. The nuclear luminosity vLv at 11.7μ is 10 times higher than that at 0.5μ . The latter wavelength needs two roughly canceling corrections: subtraction of optical light from the host galaxy, and dereddening (Ogle et al. 1997).

The conclusion is simple and expected from prior evidence: Cyg A has a moderately powerful hidden nucleus. The redshift is 0.056, and we adopt a Hubble constant of 75 km/s Mpc. This implies a vLv luminosity at 11.7μ of 9.2×10^{43} erg/sec. If the intrinsic SED is similar to those of PG quasars (Sanders et al. 1989), the 11.7μ value implies a bolometric luminosity of $16.5 \text{ vLv}(11.7\mu) \sim 1.5 \times 10^{45}$ erg/sec. For comparison the jet power is estimated several different ways (Carilli and Barthel 1996, Sikora 2001, Punsly 2001). The values are rough, but generally lie in the $\gtrsim 10^{45}$ ergs/sec range. This is consistent with the finding that jet power and optical/UV luminosity are often comparable in double radio quasars (e.g., Falcke 1995).

Thus this is a moderate luminosity broad line radio galaxy with a very high luminosity radio source. It has in fact been inferred already that Cygnus A is an over-achiever in the radio (Carilli and Barthel 1996, Barthel and Arnaud 1996). This is well explained qualitatively by the fact that it is the only known FR II radio source in a rich X-ray-emitting cluster.

3.2. M87

This radio galaxy is on the FR I-II borderline, both in morphology and in radio power (Owen et al. 2000). It is one of the majority of FR I radio galaxies with an optical/UV point source (Chiaberge et al 1999, 2000). The optical point source is tentatively ascribed to synchrotron radiation associated with the radio core (see Ford & Tsvetanov 1999). However it's not yet known whether the source is highly polarized, and whether broad emission lines are strong in either total or polarized optical/UV flux.

Our small ~ 0.3 arcsec beam isolates the innermost $\sim 25\text{pc}$ in this case, and the enclosed 11.7μ flux is 15 mJy, much lower than the large aperture measurements. The

large-aperture data from the literature leave plenty of room for waste heat from a hidden AGN, but our data do not (Fig. 3). The mid-IR luminosity is only comparable to that in the optical. In fact, much or all of the mid-IR flux could be synchrotron radiation associated with the innermost part of the jet seen in the radio and perhaps optical, so our measurement should be considered an upper limit to the dust luminosity.

Subject to the caveat that the nuclear dust emission could be entirely too cool to emit in the near-IR, this rules out a powerful hidden nucleus, and the actual upper limit on its power is of interest. The observed 11.7μ flux corresponds to $vLv = 1.0 \times 10^{41}$ erg/sec, for a distance of 15 Mpc. For the SED for the PG quasar composite of Sanders et al. 1989, a bolometric luminosity of $\sim 1.6 \times 10^{42}$ ergs/sec (e.g., the templates in Sanders et al. 1989 and Barvainis 1990). For clues to the nature of the central engine, we can compare this upper limit on any quasar-like nucleus to the power in the radio jet. A lower limit to the jet kinetic luminosity in M87 is $\sim 5 \times 10^{44}$ erg/sec (Owen et al. 2000), so the jet is by far the dominant channel for energy release.

The ADAF predictions (Reynolds et al. 1996) are for very low IR-optical-UV luminosities compared with those in the radio and X-ray. Our 11.7μ point lies at a level about equal to the optical value, but certainly our 11.7μ point may be partially or completely jet emission[§].

4. Relation to other Radio Galaxies and Conclusion

Since the M87 optical/UV flux is quite variable (e.g., Tsvetanov et al. 1998; see also the review, Ford and Tsvetanov 1999), jet synchrotron emission is a possibility. By correlating the radio synchrotron core fluxes and the optical point source fluxes in FR I radio galaxies generally, Chiaberge et al. (1999) infer that the latter are in fact beamed

synchrotron sources. A crucial test of the nature of the optical point sources is spectroscopy (and polarimetry). We hope to do this with adaptive optics, excluding most of the starlight that dominates in arcsec apertures.

Radio lobe emission is fairly isotropic, so it's easy to make lists of radio galaxies that are nearly unbiased with respect to orientation. The visibility of optical point sources in *most* of the optically dull (weak or low ionization emission line) galaxies show that there are no tori generally present which are able to obscure the optical point source (Chiaberge et al. 1999, 2000). The optical source, whatever it's nature, is tiny — if they all vary as M87 does. In that case Chiaberge et al. would probably be correct in concluding that these objects have no hidden nuclei.

However, a large minority of low ionization FR I and FR II radio galaxies show no point source, and are similar in this way to the AGN with hidden nuclei. In fact the closest FR I, Cen A, *does* have a big molecular torus (see Fig. 2 of Rydbeck et al. 1993!), and substantial evidence for a hidden nucleus as well (Capetti et al. 2000 and references therein; see also Marconi et al. 2000, Ekers and Simkin 1983, Sambruna et al. 2000 for more hidden nuclei in sources with weak and/or low ionization emission lines). As a working hypothesis we suppose that the same is true for all those without detectable optical pointlike nuclei. (Of course sensitivity of the optical/UV observations also enters in.)

Thus the FR I family is a heterogeneous one, with some contain hidden nuclei and some not. In fact at least a few are known to be quasar-like from direct spectroscopy (3C120 is well known; see also Lara et al. 1999 and Sarazin et al. 1999).

It is absolutely not the case therefore that the “nonthermal” model applies to all optical dull or low ionization radio galaxies, or to all FR I galaxies. The FR class has no apparent direct relation to the mode of energy production, consistent with much recent

evidence that the FR Is behave very much like FR IIs at VLBI scales.

^{*}Instrument reference is available at: <http://www2.keck.hawaii.edu:3636/realpublic/inst/lws/lws.html>.

[†]A table of photometric standards is available at:
http://www2.keck.hawaii.edu:3636/realpublic/inst/lws/IRTF_Standards.html.

[‡]Photometry data can be found at: <http://nedwww.ipac.caltech.edu>.

[§]It is unclear to us why the radio points, which fit the model, are taken as measurements while the (non-fitting) optical fluxes were not. Also, the Reynolds et al. figure apparently uses 3C273 as a “thermal” quasar-like template, but that object definitely has a large jet contribution in the radio and infrared (Robson et al. 1993).

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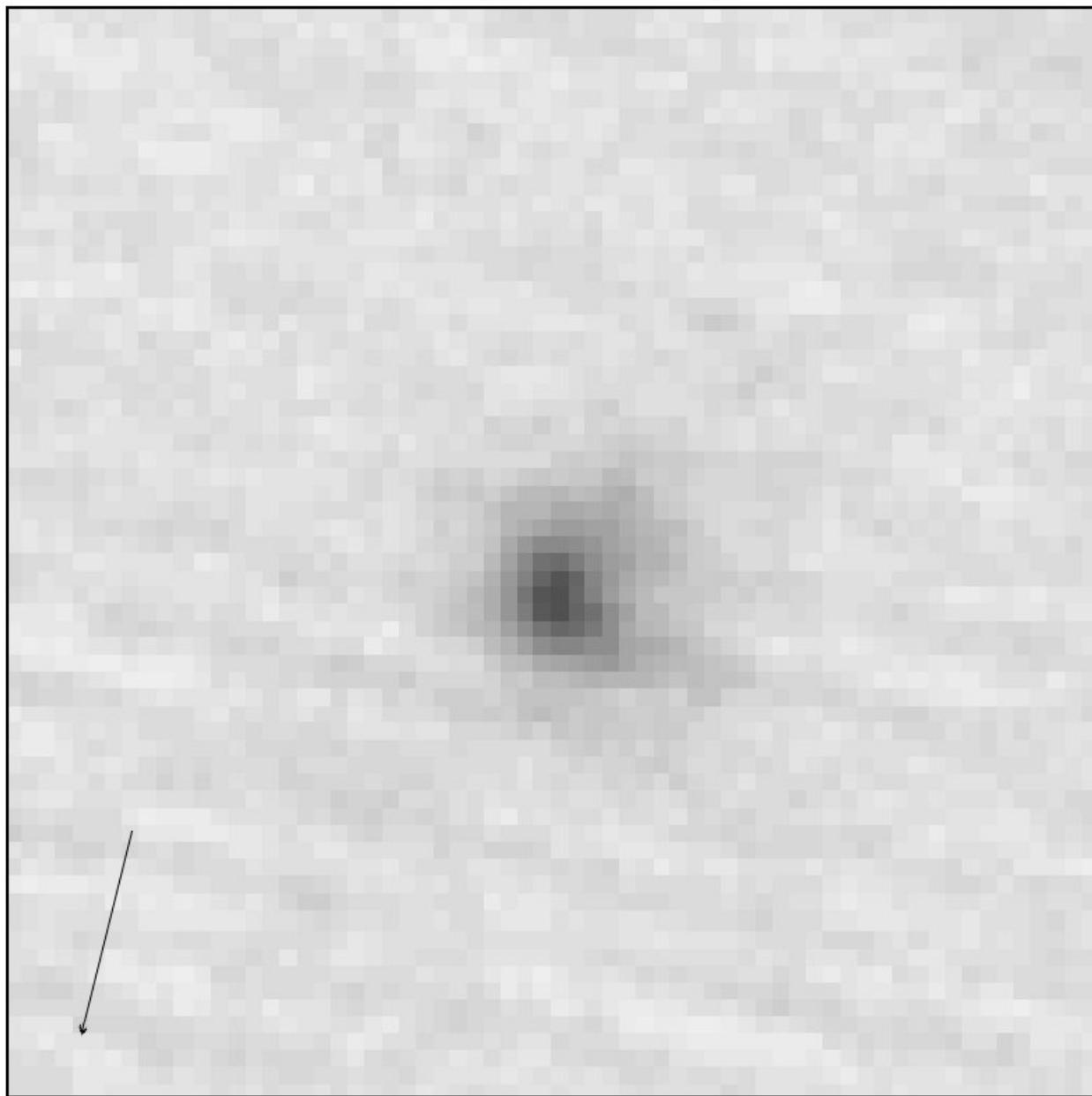
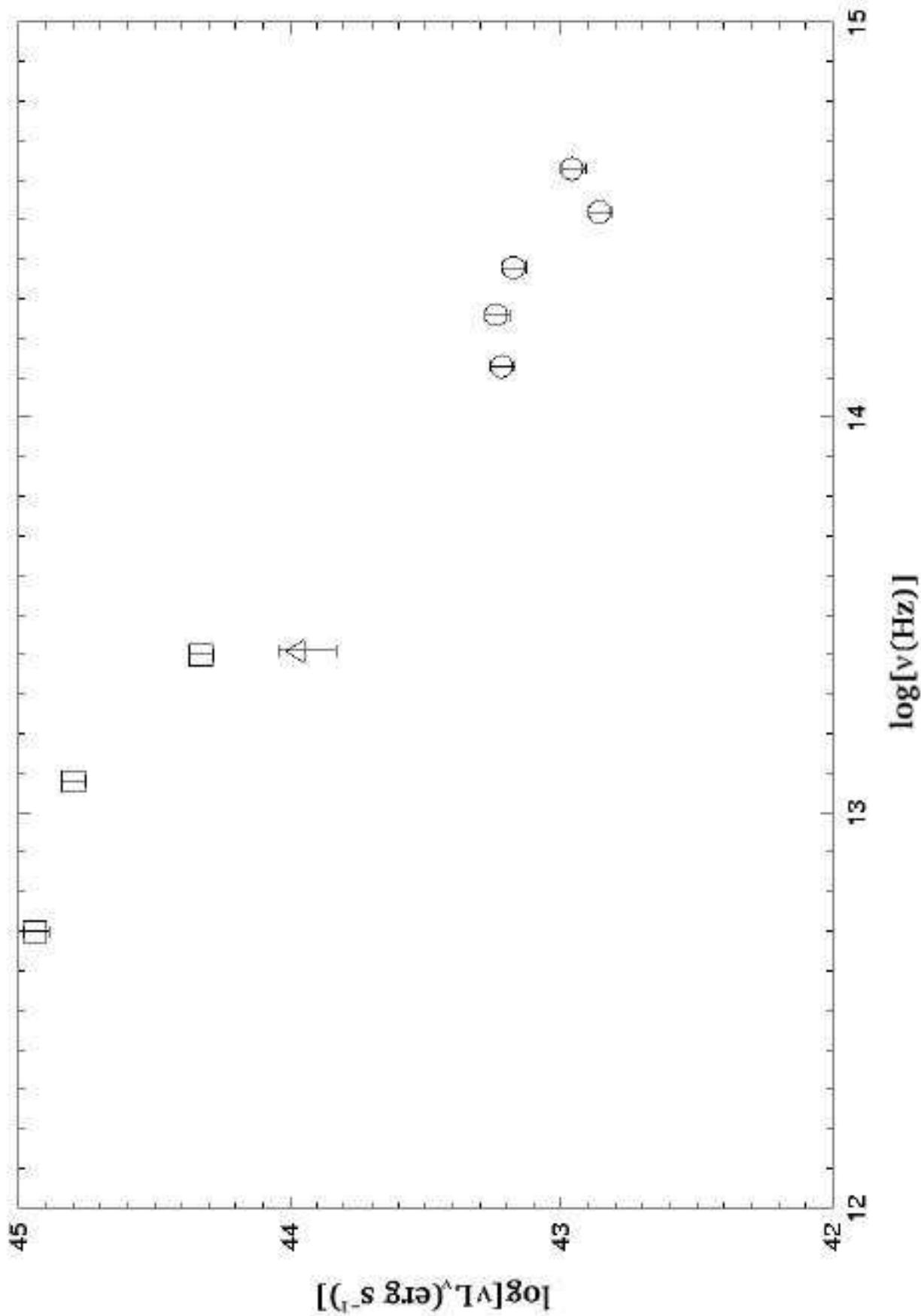


Fig. 1.— Keck LWS $11.7\mu\text{m}$ image of Cygnus A. The arrow indicates north and is 1 arcsec long.



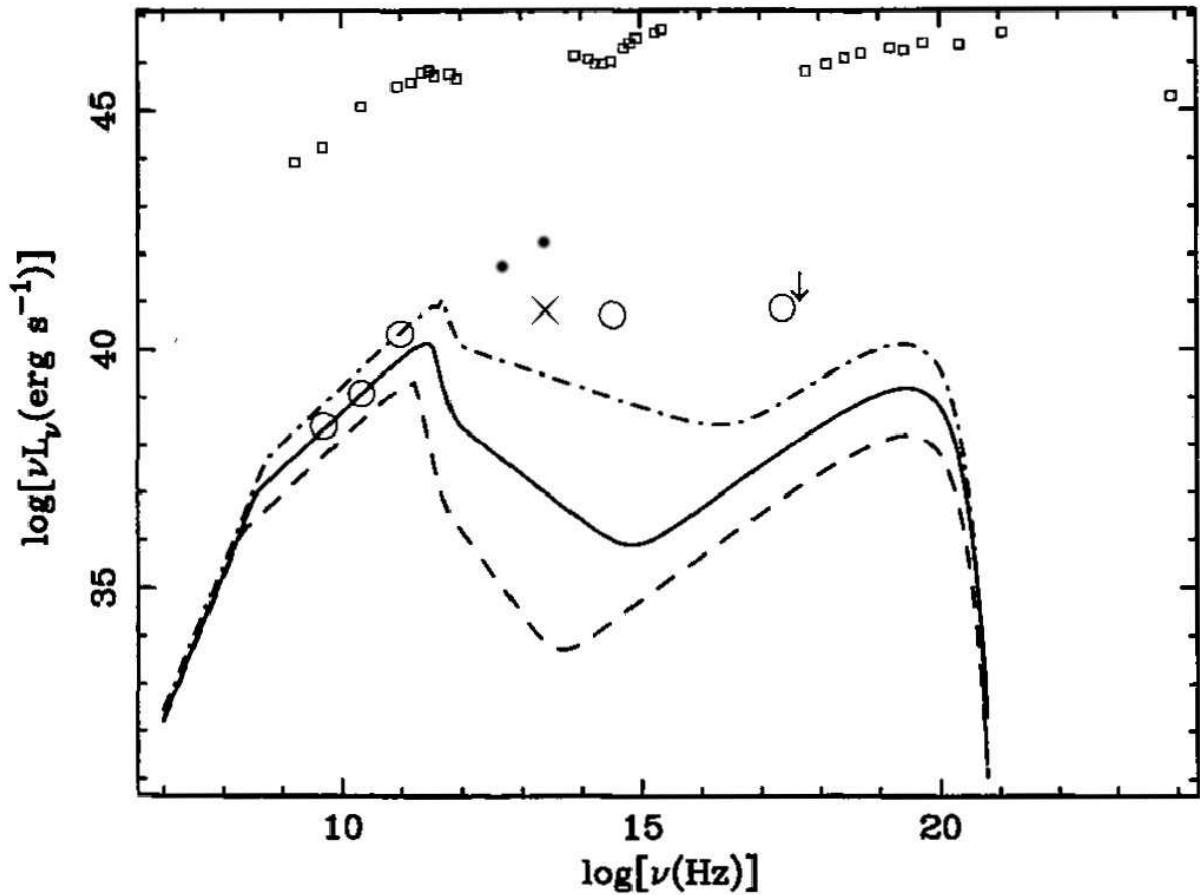


Fig. 3.— Spectral energy distribution for M87 (open circles) and 3C273 (squares), and ADAF models (lines) for various accretion rates (Reynolds et al. 1996). Additional M87 points are from the IRAS faint source catalog (Moshir et al. 1990) (solid circles) and Keck/LWS (crosses).